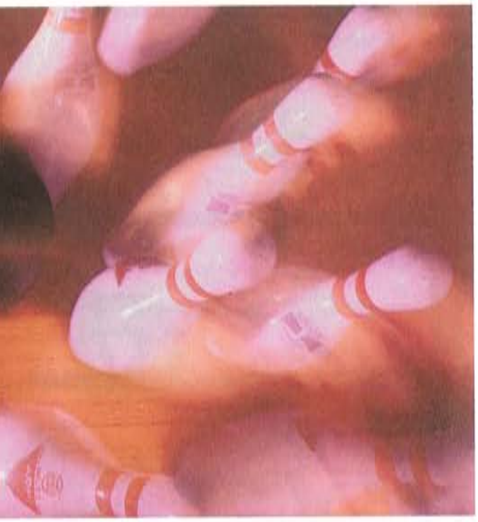
7 Momentum



Inertia *and* motion—that's momentum!

7.1 Momentum
7.2 Impulse Changes Momentum
7.3 Bouncing
7.4 Conservation of Momentum
7.5 Collisions
7.6 Momentum Vectors

Chapter 7 develops the concepts of momentum and impulse, and shows their relationship. Conservation of momentum is studied in one and two dimensions.

Have you ever wondered how a karate expert can break a stack of cement bricks with the blow of a bare hand? Or why falling on a wooden floor hurts less than falling on a cement floor? Or why follow-through is important in golf, baseball, and boxing? To understand these things, you need to recall the concept of inertia introduced and developed when we discussed Newton's laws of motion. Inertia was discussed both in terms of objects at rest and objects in motion. In this chapter we are concerned only with the concept of inertia in motion—momentum.

To introduce this chapter, you could show a *Road Runner* film. This film can be obtained from Audio-Braden. The reason this type of film is funny is that many laws of physics, especially conservation of momentum laws, are broken.

Important Term

momentum

7.1 Momentum

We know that it's harder to stop a large truck than a small car when both are moving at the same speed. We say the truck has more momentum than the car. By **momentum,** we mean *inertia in motion,* or more specifically, the mass of an object multiplied by its velocity.

$$\text{momentum} = \text{mass} \times \text{velocity}$$

or, in abbreviated notation,

$$\text{momentum} = mv$$

When direction is not an important factor, we can say

$$\text{momentum} = \text{mass} \times \text{speed}$$

which we still abbreviate mv.

We can see from the definition that a moving object can have a large momentum if it has a large mass, a high speed, or both. A moving truck has more momentum than a car moving at the same speed because the truck has more mass. But a fast car can have more momentum than a slow truck. And a truck at rest has no momentum at all.

Figure 7.1 ▲
A truck rolling down a hill has more momentum than a roller skate with the same speed, because the truck has more mass. But if the truck is at rest and the roller skate moves, then the skate has more momentum because only it has speed.

■ **Question**

Can you think of a case where the roller skate and the truck shown in Figure 7.1 would have the same momentum?

7.2 Impulse Changes Momentum

If the momentum of an object changes, either the mass or the velocity or both change. If the mass remains unchanged, as is most often the case, then the velocity changes and acceleration occurs. What produces acceleration? We know the answer is *force.* The greater the force acting on an object, the greater its change in velocity, and hence, the greater its change in momentum.

How long the force acts is also important. Apply a brief force to a stalled automobile, and you produce a change in its momentum. Apply the same force over an extended period of time and you produce a greater change in the automobile's momentum. A force sustained for a long time produces more change in momentum than does the same force applied briefly. So both force and time are important in changing momentum.

The quantity *force* × *time interval* is called **impulse.** In shorthand notation

$$\text{impulse} = Ft$$

The greater the impulse exerted on something, the greater will be the change in momentum. The exact relationship is

$$\text{impulse} = \text{change in momentum}$$

or*

$$Ft = \Delta(mv)$$

The impulse-momentum relationship helps us to analyze a variety of situations where the momentum changes. Consider the familiar examples of impulse in the following cases of increasing and decreasing momentum.

■ **Answer**

The roller skate and truck can have the same momentum if the speed of the roller skate is much greater than the speed of the truck. How much greater? As many times greater as the truck's mass is greater than the roller skate's mass. Get it? For example, a 1000-kg truck backing out of a driveway at 0.01 m/s has the same momentum as a 1-kg skate going 10 m/s. Both have momentum = 10 kg m/s.

* This relationship is derived by rearranging Newton's second law to make the time factor more evident. If we equate the formula for acceleration, $a = F/m$, with what acceleration actually is, $a = \Delta v/\Delta t$, we get $F/m = \Delta v/\Delta t$. From this we derive $F\Delta t = \Delta(mv)$. Calling Δt simply t, the time interval, $Ft = \Delta(mv)$.

Videotape: Show "Momentum" from the series *Conceptual Physics Alive!*

Important Term

impulse

Equate acceleration expressed in terms of its cause, $a = F/m$, to the kinematic definition of acceleration, $a = \Delta v/\Delta t$.

$F/m = \Delta v/\Delta t$

After replacing Δt by t for the time duration, simple rearrangement of the equation gives

$Ft = m\Delta v = \Delta(mv)$.

Consider the classic "egg drop" stunt. Students design and construct a case to hold an egg that is to be dropped from a three- or four-story building without breaking. Be sure students see, amidst the excitement and interest of the activity, that the key consideration is maximizing the time of impact in order to minimize the force of impact.

Impact is a qualitative term, not a technical term, for force.

The Best From Conceptual Physics Alive!

Definition of Momentum

Side 1
Chapter 32

Figure 7.2 ▲
The force of impact on a golf ball varies throughout the duration of impact.

Case 1: Increasing Momentum

To increase the momentum of an object, it makes sense to apply the greatest force possible for as long as possible. A golfer teeing off and a baseball player trying for a home run do both of these things when they swing as hard as possible and follow through with their swing.

The forces involved in impulses usually vary from instant to instant. For example, a golf club that strikes a golf ball exerts zero force on the ball until it comes in contact with it; then the force increases rapidly as the ball becomes distorted (Figure 7.2). The force then diminishes as the ball comes up to speed and returns to its original shape. So when we speak of such impact forces in this chapter, we mean the *average* force of impact. (Be careful to distinguish between *impact* and *impulse*. Impact refers to a *force* and is measured in newtons; impulse is *impact force* × *time* and is measured in newton-seconds.)

Case 2: Decreasing Momentum

If you were in a car that was out of control and had to choose between hitting a concrete wall or a haystack, you wouldn't have to call on your knowledge of physics to make up your mind. Common sense tells you to choose the haystack. But knowing the physics helps you to understand *why* hitting a soft object is entirely different from hitting a hard one. In the case of hitting either the wall or the haystack and coming to a stop, your momentum is decreased by the same impulse. The same impulse does not mean the same amount of force or the same amount of time; rather it means the same *product* of force and time. By hitting the haystack instead of the wall, you extend the impact time—*the time during which your momentum is brought to zero.* A longer impact time reduces the force of the impact and decreases the resulting deceleration. For example, if the time of impact is extended 100 times, the force of impact is reduced 100 times. Whenever we wish the force of impact to be small, we extend the time of impact.

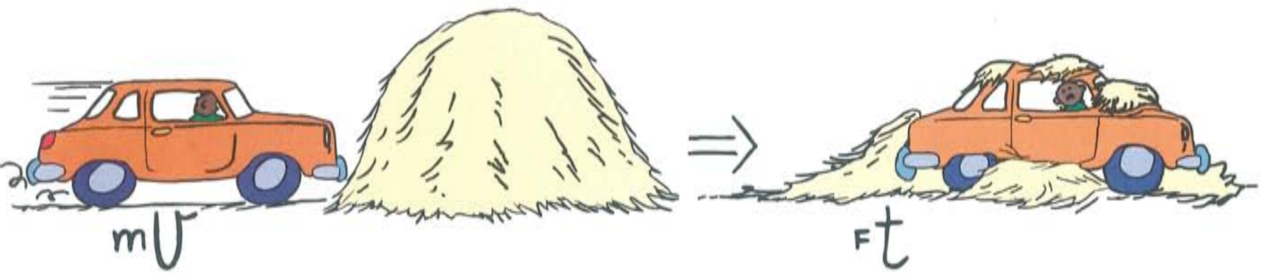
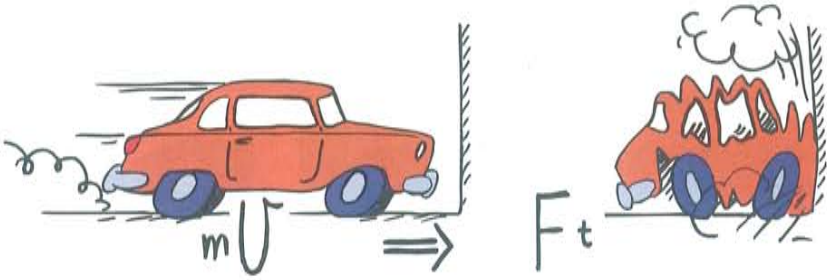


Figure 7.3 ▲
If the change in momentum occurs over a long time, the force of impact is small.

We know that a padded dashboard in a car is safer than a rigid metal one and that airbags save lives. We also know that to catch a fast-moving ball safely with your bare hand, you extend your hand forward so there's plenty of room for it to move backward after making contact with the ball. When you extend the time of impact, you reduce the force of impact.



◀ **Figure 7.4**
If the change in momentum occurs over a short time, the force of impact is large.

The Best From Conceptual Physics Alive!

Decreasing Momentum Over a Short Time

Side 1
Chapter 34

When jumping from an elevated position down to the ground, what would happen if you kept your legs straight and stiff? Ouch! Instead, you know to bend your knees when your feet make contact with the ground. By doing so you extend the time during which your momentum decreases by 10 to 20 times that of a stiff-legged, abrupt landing. The resulting force on your bones is reduced by 10 to 20 times. A wrestler thrown to the floor tries to extend his time of impact with the mat by relaxing his muscles and spreading the impact into a series of smaller ones as his foot, knee, hip, ribs, and shoulder successively hit the mat. Of course, falling on a mat is preferable to falling on a solid floor because the mat also increases the impact time.

We know a glass dish is more likely to survive if it is dropped on a carpet rather than a sidewalk because the carpet has more "give" than the sidewalk. Ask why a surface with more give makes for a safer fall and you will get a puzzled response from most people. They may simply say, "Because it gives more." However, your question is, "*Why* is a surface with more give safer for the dish?" In this case, a common explanation isn't really an explanation at all. A deeper explanation is needed.

To bring the dish or its fragments to rest, the carpet or the sidewalk must provide an impulse, which you know involves two variables—impact force and impact time. Since impact time is longer on the carpet than on the sidewalk, a smaller impact force results. The shorter impact time on the sidewalk results in a greater impact force.

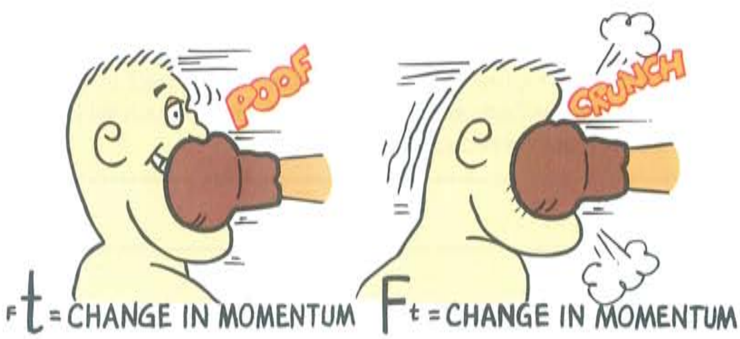


Figure 7.5 ▲
In both cases the impulse provided by the boxer's jaw must counteract the momentum of the punch. (Left) When the boxer moves away from the punch, he increases the time of impact and reduces the force of impact. (Right) When the boxer unwisely moves toward the punch, the time of impact is reduced and the force of impact is increased. Ouch!

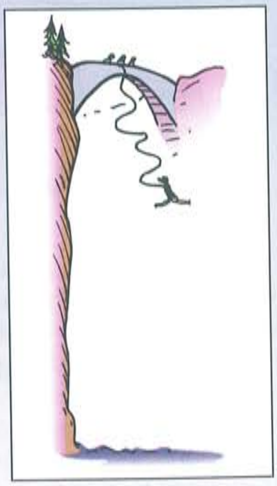
PHYSICS OF SPORTS

Bungee Jumping

The impulse-momentum relationship is put to a thrilling test during bungee jumping. Be glad the rubber cord stretches when the jumper's fall is brought to a halt, because the cord has to apply an impulse equal to the jumper's momentum in order to stop the jumper—hopefully above ground level.

Note how $Ft = \Delta(mv)$ applies here. The momentum, mv, we wish to change is the amount gained before the cord begins stretching. Ft is the impulse the cord supplies to reduce the momentum to zero.

Because the rubber cord stretches for a long time, a large time interval t ensures that a small average force F acts on the jumper. Elastic cords typically stretch to about twice their original length during the fall.



The safety net used by circus acrobats is a good example of how to achieve the impulse needed for a safe landing. The saftey net reduces the impact force on a fallen acrobat by substantially increasing the time interval of the impact.

Sometimes a difference in impact time is important even if you can't notice the give in a surface. For example, a wooden floor and a concrete floor may both seem rigid, but the wooden floor can have enough give to make quite a difference in the forces that these two surfaces exert.

Questions

1. When a dish falls, will the impulse be less if it lands on a carpet than if it lands on a hard floor?
2. If the boxer in Figure 7.5 is able to make the impact time five times longer by "riding" with the punch, how much will the force of impact be reduced?

Answers

1. No. The impulse would be the same for either surface because the same momentum change occurs for each. It is the *force* that is less for the impulse on the carpet because of the greater time of momentum change. If you answered this question incorrectly, you probably did not distinguish between impulse and impact. They sound the same, but they're not!
2. Since the time of impact increases five times, the force of impact will be reduced five times.

7.3 Bouncing

If a flower pot falls from a shelf onto your head, you may be in trouble. If it bounces from your head, you may be in more serious trouble. Why? Because impulses are greater when an object bounces. The impulse required to bring an object to a stop and then to "throw it back again" is greater than the impulse required merely to bring the object to a stop. Suppose, for example, that you catch the falling pot with your hands. You provide an impulse to reduce its momentum to zero. If you throw the pot upward again, you have to provide additional impulse. It takes a greater impulse to catch the pot *and* throw it back up than merely to catch it. This increased amount of impulse is supplied by your head if the pot bounces from it.

Bouncing does not necessarily increase impact force. That depends on impact time.

Note that bouncing involves some reversal of momentum, which means greater momentum change, and hence greater impulse. If the greater impulse is over an extended time, such as bouncing from a circus net, the impact force is small. If impulse is over a short time, such as the plant pot bouncing from your head, impact force is large.

Damage from an object colliding with a person may depend more on energy transfer than on momentum change. So, in some cases, damage can be greater in an inelastic collision which involves no bouncing.

Figure 7.6
Is the karate chop delivered in a short time or a long time? If the hand bounces upon impact, is the change in momentum greater? Is the impulse greater?

The fact that impulses are greater when bouncing takes place was used with great success during the California Gold Rush. The waterwheels used in gold mining operations were not very effective. A man named Lester A. Pelton saw that the problem had to do with

Breaking boards with your bare hand is a lot of fun. If properly done, it is neither difficult nor dangerous. Make sure you go with the wood grain. Strike with the fleshy part of the side of your hand. Do not use your knuckles. Do not have your fingers touch the board in any way.

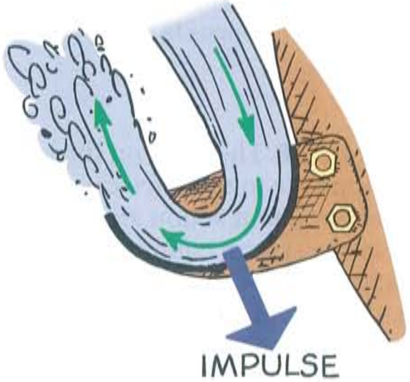


Figure 7.7
The Pelton Wheel. The curved blades cause water to bounce and make a U-turn, producing a large impulse that turns the wheel.

the flat paddles on the waterwheel. He designed a curve-shaped paddle that caused the incoming water to make a U-turn upon impact with the paddle. Because the water "bounced," the impulse exerted on the waterwheel was increased. Pelton patented his idea and probably made more money from his invention, the Pelton Wheel, than any of the gold miners earned. Physics can indeed make you rich!

Important Terms

conserved
law of conservation of momentum

The law of momentum conservation can be seen as an extension of Newton's third law, or Newton's third law can be seen as an extension of momentum conservation. Either can be viewed as basic.

7.4 Conservation of Momentum

From Newton's second law you know that to accelerate an object, a net force must be applied to it. This chapter says much the same thing, but in different language. If you wish to change the momentum of an object, exert an impulse on it.

In either case, the force or impulse must be exerted on the object by something outside the object. Internal forces won't work. For example, the molecular forces within a basketball have no effect on the momentum of the basketball, just as a push against the dashboard of a car you're sitting in does not affect the momentum of the car. Molecular forces within the basketball and a push on the dashboard are internal forces. They come in balanced pairs that cancel within the object. To change the momentum of the basketball or the car, an outside push or pull is required. If no outside force is present, no change in momentum is possible.

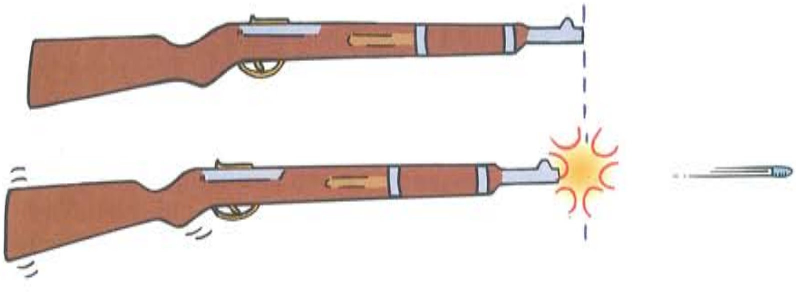


Figure 7.8 ▲
The momentum before firing is zero. After firing, the net momentum is still zero because the momentum of the rifle is equal and opposite to the momentum of the bullet.

Consider the rifle being fired in Figure 7.8. The force on the bullet inside the rifle barrel is equal and opposite to the force causing the rifle to recoil. Recall Newton's third law about action and reaction forces. These forces are internal to the system comprising the rifle and the bullet, so they don't change the momentum of the rifle-bullet system. Before the firing, the system is at rest and the momentum is zero. After the firing the net momentum, or total

momentum, is *still* zero. Net momentum is neither gained nor lost. Let's consider the effects of internal and external forces carefully.

Momentum, like the quantities velocity and force, has both direction and magnitude. It is a *vector quantity.* Like velocity and force, momentum can be canceled. So, although the bullet in the preceding example gains momentum when fired and the recoiling rifle gains momentum in the opposite direction, the rifle-bullet *system* gains none. The momenta (plural form of momentum) of the bullet and the rifle are equal in magnitude and opposite in direction. Therefore, these momenta cancel each other out for the system as a whole. No external force acted on the system before or during firing. Since no net force acts on the system, there is no net impulse on the system and there is no net change in the momentum. You can see that *if no net force or net impulse acts on a system, the momentum of that system cannot change.*

In every case, the momentum of a system cannot change unless it is acted on by external forces. A system will have the same momentum before some internal interaction as it has after the interaction occurs. When momentum, or any quantity in physics, does not change, we say it is **conserved.** The idea that momentum is conserved when no external force acts is elevated to a central law of mechanics, called the **law of conservation of momentum,** which states

> In the absence of an external force, the momentum of a system remains unchanged.

If a system undergoes changes wherein all forces are internal, as for example, in atomic nuclei undergoing radioactive decay, cars colliding, or stars exploding, the net momentum of the system before and after the event is the same.

Questions

1. Newton's second law states that if no net force is exerted on a system, no acceleration occurs. Does it follow that no change in momentum occurs?
2. Newton's third law states that the force a rifle exerts on a bullet is equal and opposite to the force the bullet exerts on the rifle. Does it follow that the *impulse* the rifle exerts on the bullet is equal and opposite to the *impulse* the bullet exerts on the rifle?

Answers

1. Yes, because no acceleration means that no change occurs in velocity or in momentum (mass × velocity). Another line of reasoning is simply that no net force means there is no net impulse and thus no change in momentum.
2. Yes, because the rifle acts on the bullet and the bullet reacts on the rifle during the same *time* interval. Since time is equal and force is equal and opposite for both, the impulse, *Ft,* is also equal and opposite for both. Impulse is a vector quantity and can be canceled.

DOING PHYSICS

Skateboards and Momentum

Stand at rest on a skateboard and throw a massive object forward or backward. Notice that you recoil in the opposite direction. The recoil is understandable because the momentum before the throw is zero and the net momentum just after the throw is also zero. Your recoil momentum is equal and opposite to the momentum of the thrown object. Observe that momentum is conserved. Now repeat the throwing motion with the same object, but this time don't let go of it. Do you still recoil? Explain.

Activity

7.5 Collisions

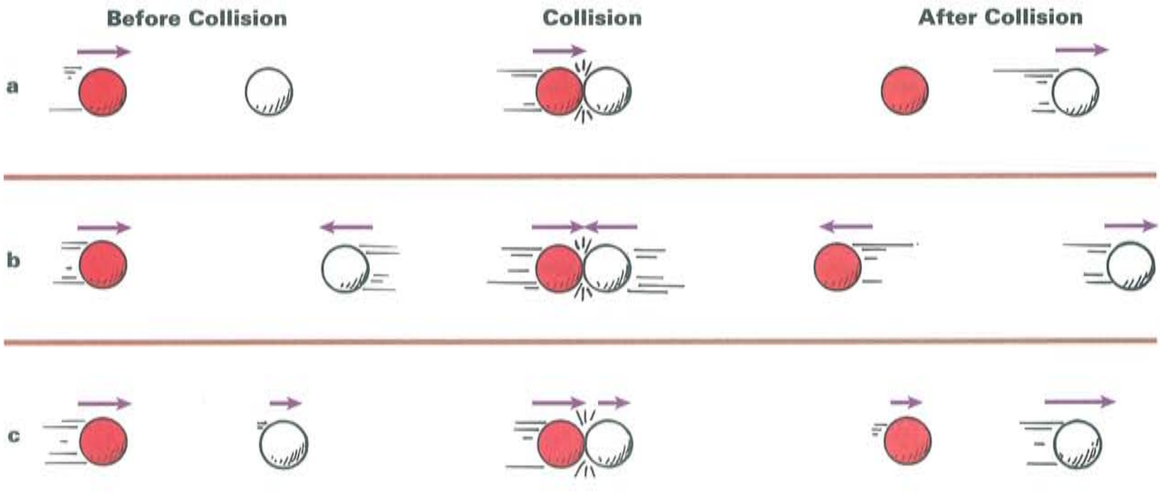
The collision of objects clearly shows the conservation of momentum. Whenever objects collide in the absence of external forces, the net momentum of both objects before collision equals the net momentum of both objects after collision.

$$\text{net momentum}_{\text{before collision}} = \text{net momentum}_{\text{after collision}}$$

Elastic Collisions

When a moving billiard ball collides head-on with a ball at rest, the first ball comes to rest and the second ball moves away with a velocity equal to the initial velocity of the first ball. We see that

Figure 7.9 ▼ Elastic collisions. (a) A moving ball strikes a ball at rest. (b) A head-on collision between two moving balls. (c) A collision of two balls moving in the same direction. In all cases, momentum is simply transferred or redistributed without loss or gain.



momentum is transferred from the first ball to the second ball. When objects collide without being permanently deformed and without generating heat, the collision is said to be an **elastic collision.** Colliding objects bounce perfectly in perfect elastic collisions, as shown in Figure 7.9. Note that the sum of the momentum vectors are the same before and after each collision.

Important Terms

elastic collision
inelastic collision

Show or describe the operation of an air track.

Inelastic Collisions

Momentum conservation holds true even when the colliding objects become distorted and generate heat during the collision. Whenever colliding objects become tangled or couple together, an **inelastic collision** occurs. The freight train cars in Figure 7.10 provide an example. Suppose the freight cars are of equal mass m, and that one car moves at 4 m/s toward the other car that is at rest. Can you predict the velocity of the coupled cars after impact? From the conservation of momentum,

$$\text{net momentum}_{\text{before collision}} = \text{net momentum}_{\text{after collision}}$$

Or in equation form,

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$

$$(m)(4\text{ m/s}) + (m)(0\text{ m/s}) = (2m)(v_{\text{after}})$$

Since twice as much mass is moving after the collision, can you see that the velocity, v_{after}, must be one half of 4 m/s? Solving for the velocity after the collision, we find $v_{\text{after}} = 2$ m/s in the same direction as the velocity before the collision, v_{before}. The initial momentum is shared by both cars without loss or gain. Momentum is conserved.

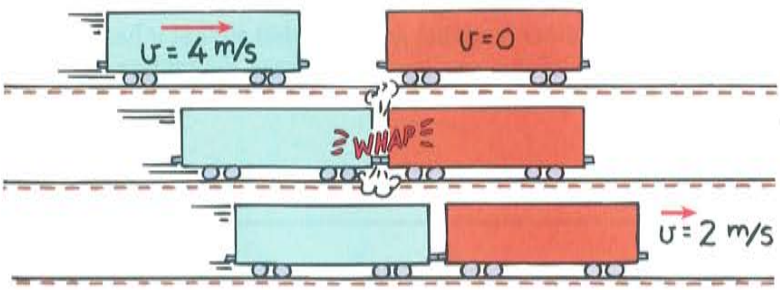


Figure 7.10 ▲
Inelastic collision. The momentum of the freight car on the left is shared with the freight car on the right.

Most collisions usually involve some external force. Billiard balls do not continue indefinitely with the momentum imparted to them. The moving balls encounter friction with the table and the air. These external forces are usually negligible during the collision, so the net momentum does not change during collision. The net momentum of two colliding trucks is the same before and just after the collision. As the combined wreck slides along the pavement, friction provides an

Figure 7.11 ▶ Conservation of momentum is nicely demonstrated with the use of an air track. Many small air jets provide a nearly frictionless cushion of air for the gliders to slide on.

impulse to decrease its momentum. Similarly, a pair of space vehicles docking in orbit have the same net momentum just before and just after contact. Since there is no air resistance in space, the combined momentum of the space vehicles after docking is then changed only by gravity.

Questions

Refer to the gliders on the air track in Figure 7.11 to answer the questions.

1. Suppose both gliders have the same mass. They move toward each other at the same speed and experience an elastic collision. Describe the motion after the collision.
2. Suppose both gliders have the same mass and stick together when they collide. The gliders move toward each other at equal speed. Describe their motion after the collision.
3. Suppose one glider is at rest and is loaded so that it has three times the mass of the moving glider. Again, the gliders stick together when they collide. Describe their motion after the collision.

Answers

1. Since the collision is elastic, the gliders reverse directions after colliding and move away from each other at a speed equal to their initial speed.
2. Before the collision, the gliders have equal and opposite momenta because their equal masses are moving in opposite directions at the same speed. The net momentum of the two gliders as a system is zero. Since momentum is conserved, their net momentum after sticking together must also be zero. They slam to a dead halt.
3. Before collision, the net momentum equals the momentum of the unloaded, moving glider. After the collision, the net momentum is the same as before, but now the gliders are stuck together and moving as a single unit. The mass of the stuck-together gliders is four times that of the unloaded glider. Thus, the postcollision velocity of the stuck-together gliders is one-fourth of the unloaded glider's velocity before collision. This velocity is in the same direction as before, since the direction as well as the amount of momentum is conserved.

Problem Solving

Consider a 6-kg fish that swims toward and swallows a 2-kg fish that is at rest. If the larger fish swims at 1 m/s, what is its velocity immediately after lunch? Momentum is conserved from the instant before lunch until the instant after (in so brief an interval, water resistance does not have time to change the momentum), so we can write

$$\text{net momentum}_{\text{before lunch}} = \text{net momentum}_{\text{after lunch}}$$

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$

$$(6\text{ kg})(1\text{ m/s}) + (2\text{ kg})(0\text{ m/s}) = (6\text{ kg} + 2\text{ kg})(v_{\text{after}})$$

$$6\text{ kg·m/s} = (8\text{ kg})(v_{\text{after}})$$

$$v_{\text{after}} = \frac{6\text{ kg·m/s}}{8\text{ kg}}$$

$$v_{\text{after}} = \frac{3}{4}\text{ m/s}$$

We see that the small fish has no momentum before lunch because its velocity is zero. Using simple algebra we see that after lunch the combined mass of the two-fish system is 8 kg and its speed is $\frac{3}{4}$ m/s in the same direction as the large fish's direction before lunch.

Suppose the small fish is not at rest but is swimming toward the large fish at 2 m/s. Now we have opposing directions. If we consider the direction of the large fish as positive, then the velocity of the small fish is –2 m/s. We pay attention to the negative sign and see that

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$

$$(6\text{ kg})(1\text{ m/s}) + (2\text{ kg})(-2\text{ m/s}) = (6\text{ kg} + 2\text{ kg})(v_{\text{after}})$$

$$(6\text{ kg·m/s}) + (-4\text{ kg·m/s}) = (8\text{ kg})(v_{\text{after}})$$

$$\frac{2\text{ kg·m/s}}{8\text{ kg}} = v_{\text{after}}$$

$$v_{\text{after}} = \frac{1}{4}\text{ m/s}$$

The negative momentum of the small fish is very effective in slowing the large fish. If the small fish were swimming at –3 m/s, then both fish would have equal and opposite momenta. Zero momentum before lunch would equal zero momentum after lunch, and both fish would come to a halt.

More interestingly, suppose the small fish swims at –4 m/s.

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$

$$(6\text{ kg})(1\text{ m/s}) + (2\text{ kg})(-4\text{ m/s}) = (6\text{ kg} + 2\text{ kg})(v_{\text{after}})$$

Emphasize the negative sign for the opposite direction. Stress the vector nature of momentum.

Problem Solving (continued)

$$(6\ \text{kg·m/s}) + (-8\ \text{kg·m/s}) = (8\ \text{kg})(v_{\text{after}})$$

$$\frac{-2\ \text{kg·m/s}}{8\ \text{kg}} = v_{\text{after}}$$

$$v_{\text{after}} = -\frac{1}{4}\ \text{m/s}$$

The minus sign tells us that after lunch the two-fish system moves in a direction opposite to the large fish's direction before lunch.

Interactive Physics™ Simulations: 15 Rocket Sled I, 16 Rocket Sled II

Perfectly elastic collisions are not common in the everyday world. We find in practice that some heat is generated during collisions. Drop a ball and after it bounces from the floor, both the ball and the floor are a bit warmer. Even a dropped superball will not bounce to its initial height. At the microscopic level, however, perfectly elastic collisions are commonplace. For example, electrically charged particles bounce off one another without generating heat; they don't even touch in the classic sense of the word. Later chapters will show that the concept of touching needs to be considered differently at the atomic level.

Review of vector rules may be helpful.

7.6 Momentum Vectors

Momentum is conserved even when interacting objects don't move along the same straight line. To analyze momentum in any direction, we use the vector techniques we've previously learned. We'll look at momentum conservation involving angles by briefly considering the three following examples.

Notice in Figure 7.12 that the momentum of car A is directed due east and that of car B is directed due north. If their momenta are

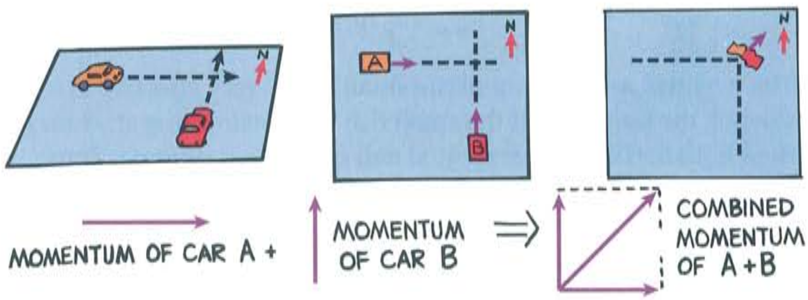
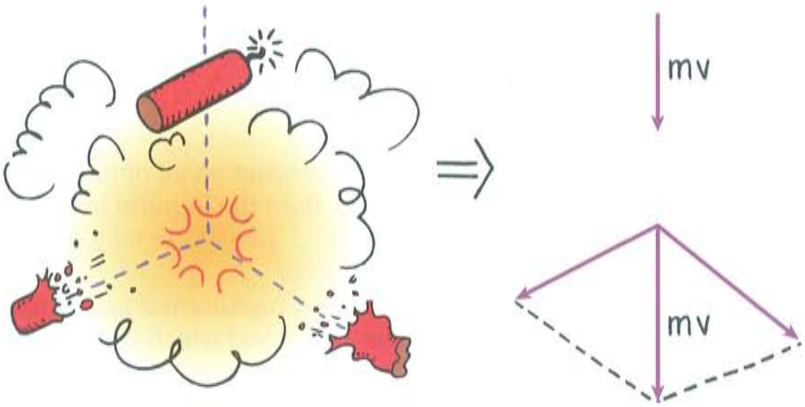


Figure 7.12 ▲
Momentum is a vector quantity. The momentum of the wreck is equal to the vector sum of the momenta of car A and car B before the collision.



For collisions involving *x* and *y* directions, $\Sigma(mv_x)_{bef} = \Sigma(mv_x)_{aft}$ and $\Sigma(mv_y)_{bef} = \Sigma(mv_y)_{aft}$. For the falling firecracker in Fig. 7.13, $\Sigma(mv_x)_{bef} = \Sigma(mv_x)_{aft} = 0$, so mv_x of piece that flies off to right $= -mv_x$ of piece that flies off to left.

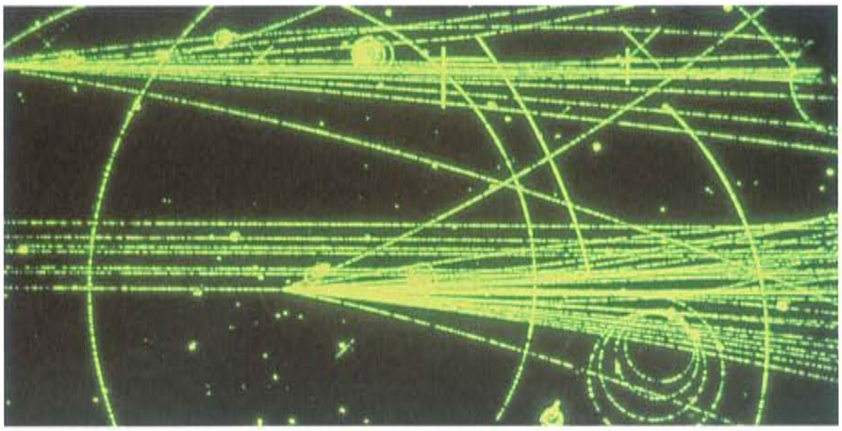
Figure 7.13 ▲
When the firecracker bursts, the vector sum of the momenta of its fragments add up to the firecracker's momentum just before bursting.

equal in magnitude, after colliding their combined momentum will be in a northeast direction with a magnitude $\sqrt{2}$ times the momentum either vehicle had before the collision (just as the diagonal of a square is $\sqrt{2}$ times the length of a side).

Figure 7.13 shows a falling firecracker that explodes into two pieces. The momenta of the fragments combine by vector rules to equal the original momentum of the falling firecracker.

Figure 7.14 shows tracks made by subatomic particles in a spark chamber. The mass of these particles can be computed by applying both the conservation of momentum and conservation of energy laws—the conservation of energy law will be discussed in the next chapter. The conservation laws are extremely useful to experimenters in the atomic and subatomic realms. A very important feature of their usefulness is that forces do not show up in the equations. Forces in collisions, however complicated, are not a concern.

Conservation of momentum and, as the next chapter will discuss, conservation of energy, are the two most powerful tools of mechanics. Their application yields detailed information that ranges from understanding the interactions of subatomic particles to entire galaxies.



◄ **Figure 7.14**
Momentum is conserved for the high-speed elementary particles, as shown by the tracks they leave in a spark chamber. The relative mass of the particles is determined by, among other things, the paths they take after collision.

7 Chapter Review

For fuller explanations, see the TE notes in the front of this book.

Concept Summary

The momentum of an object is the product of its mass and its velocity.

- The change in momentum depends on the force that acts and the length of time it acts.
- Impulse is average force multiplied by the time during which it acts.
- The impulse exerted on something is equal to the change in momentum it produces.

The law of conservation of momentum states that momentum is conserved when there is no net external force.

- When objects collide in the absence of external forces, momentum is conserved no matter whether the collision is elastic or inelastic.

Momentum is a vector quantity.

- Momenta combine by vector rules.

Important Terms

conserved (7.4)
elastic collision (7.5)
impulse (7.2)
inelastic collision (7.5)
law of conservation of momentum (7.4)
momentum (7.1)

Review Questions

Recall of key chapter ideas

1. Distinguish between *mass* and *momentum.* Which is inertia and which is inertia in motion? (7.1) Mass—inertia; momentum—inertia in motion
2. **a.** Which has the greater mass, a heavy truck at rest or a rolling skateboard? Truck

   b. Which has greater momentum? (7.1) Moving skateboard
3. Distinguish between *impact* and *impulse.* Which designates a force and which is force multiplied by time? (7.2) Impact—force; impulse—force × time
4. When the force of impact on an object is extended in time, does the impulse increase or decrease? (7.2) Same force for longer time = greater impulse
5. Distinguish between *impulse* and *momentum.* Which is force × time and which is inertia in motion? (7.2) Impulse—force × time; momentum—moving inertia
6. Does impulse equal momentum, or a *change* in momentum? (7.2) Impulse = change in momentum
7. For a constant force, suppose the duration of impact on an object is doubled.

   a. How much is the impulse increased? Doubles

   b. How much is the resulting change in momentum increased? (7.2) Doubles
8. In a car crash, why is it advantageous for an occupant to extend the time during which the collision takes place? (7.2) More time, less force
9. If the time of impact in a collision is extended by four times, how much does the force of impact change? (7.2) Divide by four
10. Why is it advantageous for a boxer to ride with the punch? Why should he avoid moving into an oncoming punch? (7.2) More *t*, less *F*; less *t*, more *F*
11. Visualize yourself on a skateboard.

    a. When you throw a ball, do you experience an impulse? Yes

    b. Do you experience an impulse when you catch a ball of the same speed? Yes

    c. Do you experience an impulse when you catch it and then throw it out again? Yes

    d. Which impulse is greatest? (7.3) When catching and throwing it out again

12. Why is more impulse delivered during a collision when bouncing occurs than during one when it doesn't? (7.3) Momentum change is more so impulse is more.

13. Why is the Pelton Wheel an improvement over paddle wheels with flat blades? (7.3) More change in fluid momentum, more impulse

14. In terms of momentum conservation, why does a gun kick when fired? (7.4) Gun's momentum equal and opposite to bullet's

15. What does it mean to say that momentum is conserved? (7.4) Same before and after interaction

16. Distinguish between an elastic and an inelastic collision. (7.5) Elastic, bounces; inelastic, sticks

17. Imagine that you are hovering next to the space shuttle in an earth-orbit and your buddy of equal mass who is moving at 4 km/h with respect to the ship bumps into you. If he holds onto you, how fast do you both move with respect to the ship? (7.5) Double mass moves at half speed, 2 km/h

18. Is momentum conserved for colliding objects that are moving at angles to one another? Explain. (7.6) Yes. Resulting motions follow vector rules.

Plug and Chug

Math reinforcement—conceptual development through applied problem solving

1. **a.** What is the momentum of an 8-kg bowling ball rolling at 2 m/s? $8\text{ kg} \times 2\text{ m/s} = 16\text{ kg}\cdot\text{m/s}$

   b. If the bowling ball rolls into a pillow and stops in 0.5 s, calculate the average force it exerts on the pillow. $F = \Delta mv/t = 16/0.5 = 32\text{ N}$

   c. What average force does the pillow exert on the ball? Same

2. **a.** What is the momentum of a 50-kg carton that slides at 4 m/s across an icy surface? $50\text{ kg} \times 4\text{ m/s} = 200\text{ kg}\cdot\text{m/s}$

   b. The sliding carton skids onto a rough surface and stops in 3 s. Calculate the force of friction it encounters. $F = \Delta mv/t = 200/3 = 66.6\text{ N}$

3. **a.** What impulse occurs when an average force of 10 N is exerted on a cart for 2.5 s? $10\text{ N} \times 2.5\text{ s} = 25\text{ N}\cdot\text{s}$

   b. What change in momentum does the cart undergo? 25 kg•m/s

   c. If the mass of the cart is 2 kg and the cart is initially at rest, calculate its final speed. 12.5 m/s

4. A 2-kg blob of putty moving at 3 m/s slams into a 2-kg blob of putty at rest.

   a. Calculate the speed of the two stuck-together blobs of putty immediately after colliding. 1.5 m/s

   b. Calculate the speed of the two blobs if the one at rest was 4 kg. $v = (6\text{ kg}\cdot\text{m/s})/(2 + 4)\text{ kg} = 1\text{ m/s}$

Think and Explain

Conceptual development through applied critical thinking

1. When you ride a bicycle at full speed and the bike stops suddenly, why do you have to push hard on the handlebars to keep from flying forward? Provides impulse to decrease your momentum

2. In terms of impulse and momentum, why are air bags in automobiles a good idea? More contact time, less force

3. Why is it difficult for a firefighter to hold a hose that ejects large amounts of water at high speed? Hose recoils from ejected water like a rocket.

4. You can't throw a raw egg against a wall without breaking it, but you can throw it at the same speed into a sagging sheet without breaking it. Explain. Longer contact time, less force

5. Suppose you roll a bowling ball into a pillow and the ball stops. Now suppose you roll it against a spring and it bounces back with an equal and opposite momentum.

   a. Which object exerts a greater impulse, the pillow or the spring? Spring

   b. If the time it takes the pillow to stop the ball is the same as the time of contact of the ball with the spring, how do the average forces each exerts on the ball compare? Double for spring because double Δmv

6. If you topple from your treehouse, you'll continuously gain momentum as you fall to the ground below. Doesn't this violate the conservation of momentum? Defend your answer. If system is you + world, momentum is conserved.

7. A bug and the windshield of a fast-moving car collide. Indicate whether each of the following statements is true or false.

   a. The forces of impact on the bug and on the car are the same size. True

   b. The impulses on the bug and on the car are the same size. True

   c. The change in speed of the bug and the car is the same. False

   d. The changes in momentum of the bug and of the car are the same size. True

8. What difference in kick would you expect in firing a bullet versus firing a blank cartridge from the same gun? Explain. More from fired bullet, because more Δmv

9. A group of playful astronauts, each with a bag full of balls, form a circle as they free-fall in space. Describe what happens when they begin tossing balls simultaneously to one another. Because of recoil, the circle widens.

10. A proton from an accelerator strikes an atom. An electron is observed flying forward in the same direction the proton was moving and at a speed much greater than the speed of the proton. What conclusion can you draw about the relative mass of a proton and an electron? An electron has less mass.

Think and Solve

Math reinforcement—variable substitution and equation solving

1. A 1000-kg car moving at 20 m/s slams into a building and comes to a halt. Consider questions **a** and **b** below. Which question can be answered using the given information and which one cannot be answered? Explain.

   a. What impulse acts on the car? 20 000 N•s

   b. What is the force of impact on the car? Can't say unless impact time is known

2. A car with a mass of 1000 kg moves at 20 m/s. What braking force is needed to bring the car to a halt in 10 s? $F = \Delta mv/t = (1000 \times 20)/10 = 2000$ N

3. Assume an 8-kg bowling ball moving at 2 m/s bounces off a spring at the same speed that it had before bouncing.

   a. What is its momentum of recoil? 8 kg × (–2 m/s) = –16 kg•m/s

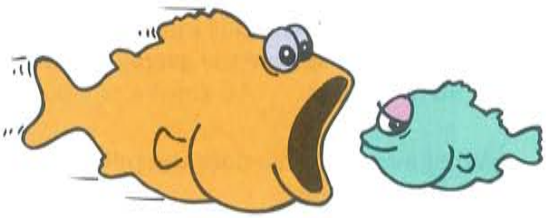
   b. What is its change in momentum? (*Hint:* What is the change in temperature when something goes from 1° to –1°?) 32 kg•m/s

   c. If the interaction with the spring occurs in 0.5 s, calculate the average force the spring exerts on it. $F = \Delta mv/t = 32/0.5 = 64$ N

   d. Compare this force with the force on the pillow in Plug and Chug 1. Double, since Δmv is double

4. A railroad diesel engine weighs four times as much as a freight car. If the diesel engine coasts at 5 km/h into a freight car that is at rest, how fast do the two coast after they couple? 4 km/h

5. A 5-kg fish swimming 1 m/s swallows an absent-minded 1-kg fish at rest. What is the speed of the large fish immediately after lunch? What would its speed be if the small fish were swimming toward it at 4 m/s? 5/6 m/s; 1/6 m/s



6. Comic-strip hero Superman meets an asteroid in outer space and hurls it at 100 m/s. The asteroid is a thousand times more massive than Superman is. In the strip, Superman is seen at rest after the throw. Taking physics into account, what would be his recoil speed? What is this in miles per hour? v = 100 000 m/s; 224 000 mi/h